9.4 Design Procedure

9.4.1 Survey Accuracy (Computation Method)

The design for a stream crossing system requires a comprehensive engineering approach that includes formulation of alternatives, data collection, selection of the most cost effective alternative according to established criteria and documentation of the final design.

Water surface profiles are computed for a variety of technical uses including:

- flood insurance studies
- flood hazard mitigation investigations
- drainage crossing analysis
- longitudinal encroachments

The completed profile can affect the highway bridge design and is the mechanism for determining the effect of a bridge opening on upstream water levels. The step backwater profile method is commonly used for developing water surface profile. Errors associated with computing water surface profiles with the step backwater profile method can be classified as:

- data estimation errors resulting from incomplete or inaccurate data collection and inaccurate data estimation
- errors in accuracy of energy loss calculations depending on the validity of the energy loss equation employed and the accuracy of the energy loss coefficients
- inadequate length of stream reach investigated
- computational errors due to poor cross sectional spacings. These errors can be significant due to inaccurate integration of the energy loss-distance relationship that is the basis for profile computations. These errors may be reduced by adding interpolated or actual sections to the analysis.

9.4.2 Design Procedure Outline

Although the scope of the project and individual site characteristics make each design an unique one, this procedure shall be applied unless indicated otherwise by the Hydraulics and Drainage section.

I. Data Collection
  A. Survey
    - Topography/channel cross sections
    - Geology
    - Highwater marks
    - History of debris accumulation, ice and scour
    - Review of hydraulic performance of existing structures
    - Maps, aerial photographs
    - Rainfall and stream gage records
    - Field reconnaissance
  B. Studies by other agencies
    - FEMA Flood Insurance Studies
    - Federal Floodplain Studies by the ACOE, NRCS, etc.

  - Local Floodplain Studies
  - Hydraulic performance of existing bridges
  - ConnDEP Inland Water Resources Division
  - Stream Channel Encroachment Line Reports
- C. Influences on hydraulic performance of site
  - Other streams, reservoirs, water intakes
  - Structures upstream or downstream
  - Natural features of stream and floodplain
  - Channel modifications upstream or downstream
  - Floodplain encroachments
  - Sediment types and bed forms (Scour, Site Data, Level I Qualitative Analysis — FHWA HEC-20)
- D. Environmental impact
  - Existing bed or bank instability
  - Floodplain land use and flow distribution
  - Environmentally sensitive areas (fisheries, wetlands, etc.)
  - Level I Qualitative Analysis (FHWA HEC-20)
- E. Site-specific Design Criteria
  - Preliminary risk assessment
  - Application of ConnDOT criteria

II. Hydrologic Analysis (See Chapter 3, Section 3.5, Design Development and Chapter 6, Hydrology.)
- A. Watershed morphology
  - Drainage area (attached map)
  - Watershed and stream slope
  - Channel geometry
- B. Hydrologic computations
  - Discharge and frequency for historical flood that complements the high water marks used for calibration
  - Discharges for specified frequencies

III. Hydraulic Analysis (See Chapter 3, Section 3.5, Design Development and Section 9.4.3.)
- A. Computer model calibration and verification
- B. Hydraulic performance for existing conditions – including floodway analysis, if appropriate
- C. Hydraulic performance of proposed designs – including floodway analysis, if appropriate
- D. Hydraulic analysis of “natural” condition
- E. Scour computations (See Section 9.5 and Appendix B – Amended Local Abutment Scour Equations for Connecticut)

IV. Selection of Final Design
- A. Risk assessment/Least-cost alternative (LTEC) (if required see Section 9.6.7)
- B. Measure of compliance with established hydraulic criteria
- C. Consideration of environmental and social criteria
- D. Design details such as riprap, scour abatement, river training

V. Documentation (See Section 9.3.9)
   A. Complete project records, permit applications, etc.
   B. Complete correspondence and reports
   C. Requirements in the ConnDEP IWRD “Model Hydraulic Analysis” document for report format
   D. Hydraulic Data Sheet presented in Appendix A.

9.4.3 Hydraulic Performance Of Bridges

The stream-crossing system is subject to either free-surface flow or pressure flow through one or more bridge openings with possible embankment overtopping. These hydraulic complexities should be analyzed using a computer program such as HEC-RAS, HEC-2 or WSPRO unless indicated otherwise by the Hydraulics and Drainage section. The hydraulic variables and flow types are defined in Figures 9-1 and 9-2.

Backwater (h_1) is measured relative to the normal water surface elevation without the effect of the bridge at the approach cross section (Section 1). Backwater is the result of contraction and re-expansion head losses and head losses due to bridge piers. Backwater can also be the result of a "choking condition" in which critical depth is forced to occur in the contracted opening with a resultant increase in depth and specific energy upstream of the contraction. This is illustrated in Figure 9-2.

The following are the three types of flow which may be encountered in bridge waterway design illustrated in Figure 9-2:

- Type I consists of subcritical flow throughout the approach, bridge and exit cross sections and is the most common condition encountered in practice.
- Type IIA and IIB both represent subcritical approach flows which have been choked by the contraction resulting in the occurrence of critical depth in the bridge opening. In Type IIA the critical water surface elevation in the bridge opening is lower than the undisturbed normal water surface elevation. In the Type IIB it is higher than the normal water surface elevation and a weak hydraulic jump immediately downstream of the bridge contraction is possible.
- Type III flow is supercritical approach flow and remains supercritical through the bridge contraction. Such a flow condition is not subject to backwater unless it chokes and forces the occurrence of a hydraulic jump upstream of the contraction.

9.4.4 Methodologies

No single method is ideally suited for all situations. If a satisfactory computation cannot be achieved with a given method, an alternate method should be attempted. However, it has been found that, with careful attention to the setup requirements of each method, essentially duplicate results can usually be achieved using both momentum and energy methods.

Momentum

- HEC-2

The Corps of Engineers HEC-2 model uses a variation of the momentum method in the special bridge routine when there are bridge piers. The momentum equation between cross sections 1 and 3 is used to detect Type II flow and solve for the upstream depth in this case with critical depth in the bridge contraction.

This model has been used for the majority of the flood insurance studies performed under the National Flood Insurance Program (NFIP). However, some feel that the bridge analysis routines in HDS-1 and WSPRO may yield a better definition of actual hydraulic performance.

•HEC-RAS

The Corps of Engineers Hydrologic Engineering Center (HEC) has developed the HEC-RAS (River Analysis System) program package. It operates under WINDOWS and has full graphic support. The finished package includes all the features inherent to HEC-2 and WSPRO plus program selected friction slope methods, mixed flow regime capability, automatic "n" value calibration, ice cover, quasi 2-D velocity distribution, superelevation around bends, bank erosion, riprap design, stable channel design, sediment transport calculations and scour at bridges. In addition to momentum balance, other methods are available in HEC-RAS for computing losses through bridges. These methods include the Energy Equation (standard step method), Yarnell equation and FHWA WSPRO method.

Energy

•HDS-1

The method developed by FHWA described in HDS-1 is an energy approach with the energy equation written between cross sections 1 and 4 as shown in Figure 9-1 for Type I flow. The backwater is defined in this case as the increase in the approach water surface elevation relative to the normal water surface elevation without the bridge.

This model utilizes a single typical cross section to represent the stream reach from points 1 to 4 on Figure 9-1. It also requires the use of a single energy gradient. This method is no longer recommended for final design analysis of bridges due to its inherent limitations but it may be useful for preliminary analysis and training. Studies performed by the Corps of Engineers for the FHWA show the need to utilize a multiple cross section method of analysis in order to achieve reasonable stage-discharge relationships at a bridge.

•WSPRO

WSPRO combines step-backwater analysis with bridge backwater calculations. This method allows for pressure flow through the bridge, embankment overtopping and flow through multiple openings and culverts. The bridge hydraulics still rely on the energy principle, but there is an improved technique for determining approach flow lengths and the introduction of an expansion loss coefficient. The flow-length improvement was found necessary when approach flows occur on very wide heavily-vegetated floodplains. The program also greatly facilitates the hydraulic analysis required to determine the least-cost alternative.

Physical Modeling

Complex hydrodynamic situations defy accurate or practicable mathematical modeling. Physical models should be considered when:

- hydraulic performance data are needed that cannot be reliably obtained from mathematical modeling

- risk of failure or excessive over-design is unacceptable
- research is needed

The constraints on physical modeling are:

- size(scale)
- cost
- time

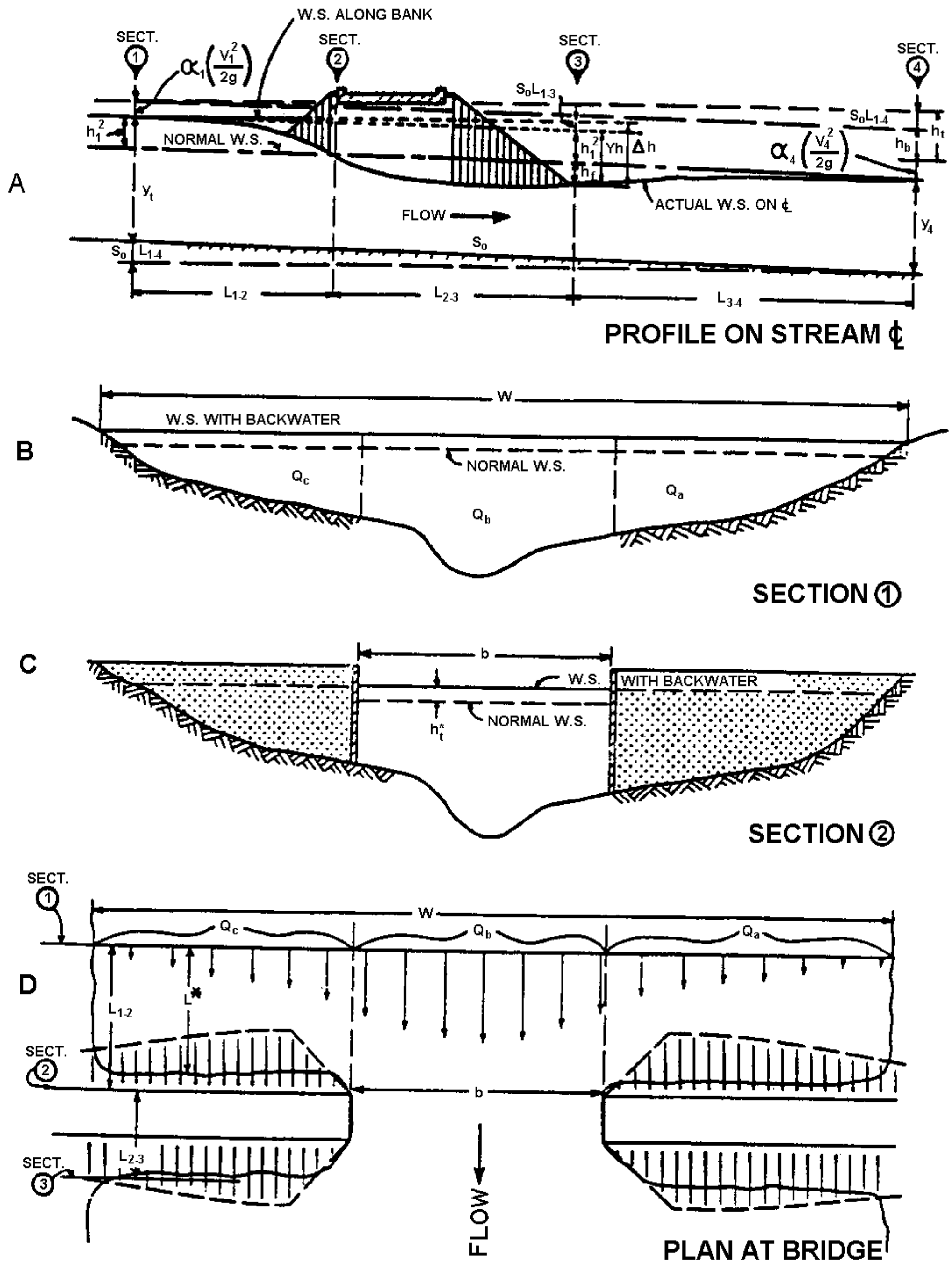

Figure 9-1 Bridge Hydraulics Definition Sketch

Source: HDS-1

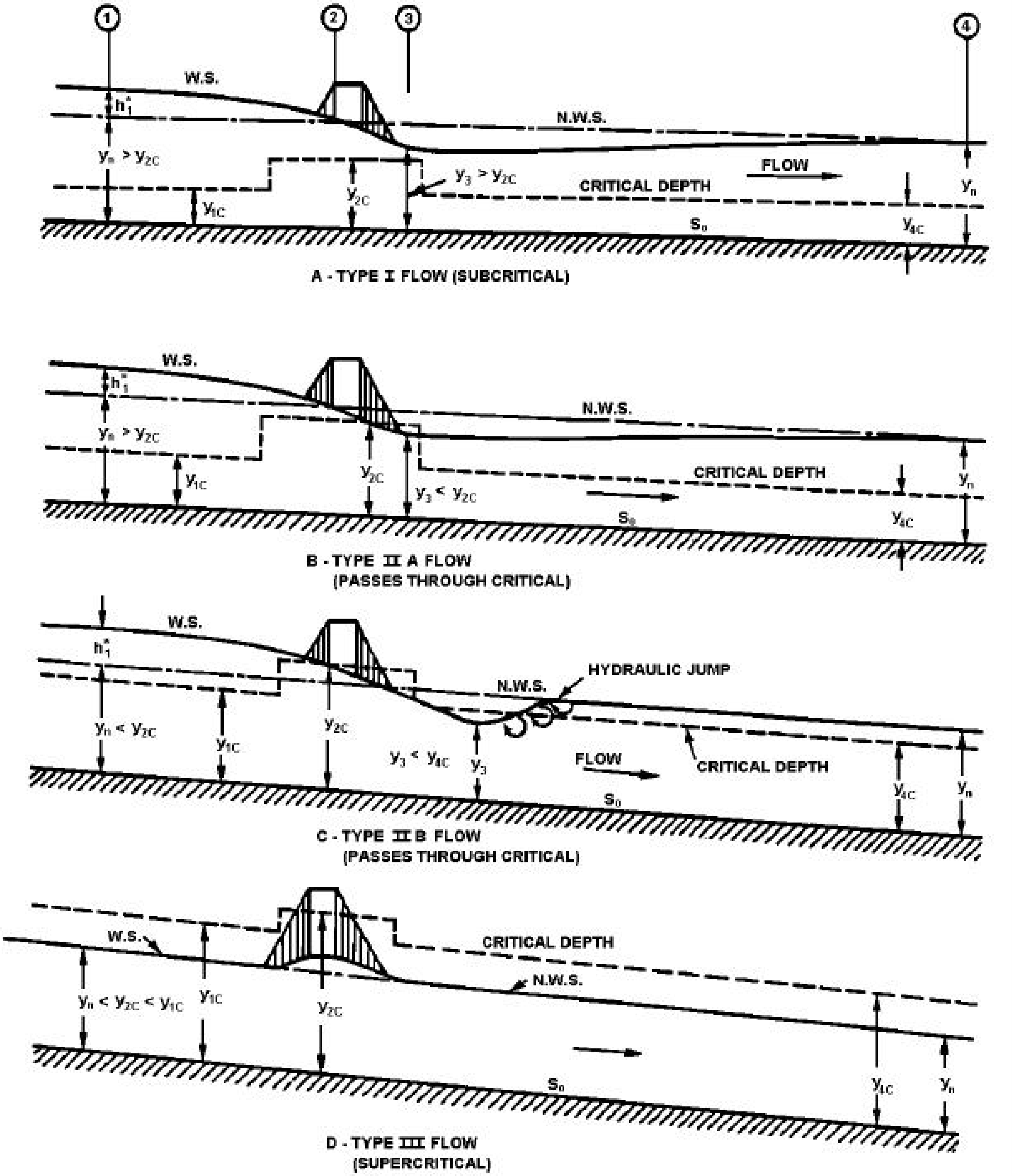

Figure 9-2 Bridge Flow Types

Source: HDS-1

9.4.5 Coastal or Tidally Influenced Waterways

Introduction

Tidal flow, both at flood stage and under normal conditions, may be restricted in its entrance into marshes and estuaries. Natural narrow and/or shallow passageways as well as man-made restrictions may be present. These restrictions will affect the timing cycle of high and low water, which, in turn, may affect the environmental quality of the marsh or estuary and its adjacent wetlands. The highway designer should be aware of these potential impacts, particularly when planning a new facility.

The computerized design tools for bridges of tidally influenced waterways lags behind similar designs on riverine systems. The complicated phenomenon is difficult to simulate for several reasons, but primarily due to the waterway's unsteady nature. Coastal waterways are subject to storm surges and astronomical tides which play an important role in hydraulic behavior. The collection of adequate data to represent the actual condition also adds to the complexity of the problem. Data such as flows and storm surge description may be very difficult to estimate. For small bridges, complex modeling may not be cost effective since the cost of the study may exceed the cost of the bridge.

Design of a tidal crossing requires consideration of the following features that do not apply in most inland river situations:

- The size of the tidal waterway opening can modify the tidal regime and the associated tidal discharges
- Currents and ice may flow in either direction
- Ice frozen to piers and piles may result in large vertical forces as tides rise and fall
- Structural elements may be subject to wave heights and forces
- Scour can be enhanced by periodic current reversals

Presently there is no standard procedure for the design of tidally influenced waterways. In many cases, the bridge hydraulic opening is designed to extend across the normal open water section. This may be an appropriate design from an economic standpoint; since the total cost of a larger bridge approximates the cost of a smaller bridge considering approach embankments and abutment protection measures. This design is also desirable from an environmental perspective since it results in minimal environmental impacts. In most designs, the extent of detail in the analysis must be commensurate with the project size or potential environmental impacts. However, analytical evaluation of the opening is often required and is necessary when a full crossing cannot be considered or when the existing structure exhibits hydraulic problems. The complexities of these analyses lend themselves to computer modeling. Ongoing research is being conducted to develop standard procedures for the design of coastal waterways.

Computer Modeling

Existing models cover a wide range from simple analytical solutions to heavily computer intensive numerical models. Some models deal only with flows through inlets, while others describe general one-dimensional or two-dimensional flow in coastal areas. A higher level includes hurricane or other storm behavior and predicts the resulting storm surges.

One-dimensional models are the most commonly used models because they demand less data and computer time than the more comprehensive models. Most analyses for tidal streams are conducted with steady state models where the tidal effects are not simulated. This may be an adequate approach if the crossing is located inland from the mouth where the tidal effects are insignificant. Computer modeling for steady state hydraulics is generally preformed with the Corps of Engineers HEC-2 or HEC-RAS or, the NRCS WSP-2 or the U.S. Geological Service – FHWA WSPRO (HY-7).

In the event that tidal fluctuations are significant, simulation of the unsteady hydraulics is more appropriate. Dynamic modeling is recommended when complex geomorphic or hydraulic conditions make the above listed methods unusable or when simplifying assumptions are violated to such a degree that the results are overly conservative. Complex geomorphic conditions include anabranching or multiple channel inlets or estuaries, large flood plain areas constricted by main channel and relief bridges, and complex channel geometry near bridges. For estuaries with large vegetated flood plains, where the simple tidal prism method is overly conservative due to high flow resistance, dynamic modeling is most appropriate. Dynamic modeling is also most appropriate in the case of large bays where an assumed level water surface is overly conservative.

Dynamic models account for all forms of energy loss. Dynamic models that include hydraulic structures are UNET and FESWMS-2DH.

UNET is a powerful unsteady flow one-dimensional model that computes flow through a bifurcating or branching network of channels. UNET also includes storage areas and a wide variety of hydraulic structures. These features make this model useful in tidal and unsteady riverine applications where bridge hydraulics are an important component. UNET (HEC 1996) was developed by Dr. Robert L. Barkau. Under agreement with Dr. Barkau, the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC) maintains, distributes and provides training for UNET.

Other one dimensional hydrodynamic models such as DYNLET 1, also developed by the ACOE, may be suitable for the analysis and design of a tidal crossing. However, UNET is preferred since the unsteady flow equation solver of this program will eventually be incorporated into HEC-RAS.

Where complicated hydraulics exist, for instance as in wide floodplains with interlaced channels or where flow is not generally in one direction, a one-dimensional model may not represent adequately the flow phenomena and a two-dimensional model is more appropriate. The FESWMS program can be used as described in the section entitled "2-Dimensional Modeling." An acceptable alternative to the FESWMS program may be the RMA2 model developed by the ACOE.

Two-dimensional models require considerable time for model calibration. Thus, they do not lend themselves for analysis of smaller structure sites.

The hydraulic engineer is responsible for determining the most suitable method for analyzing tidal structures. The decision should be made early in the design phase with approval from the Hydraulics and Drainage Section.